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DIAGNOSTIC STUDIES OF EXPLOSIVE MARITIME CYCLOGENESIS

Final Technical Report

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Funding for a three-year period originally was requested to conduct diagnostic studies of the dynamics of explosively deepening maritime cyclones in the western North Atlantic region in conjunction with the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA). The focus of the proposed diagnostic studies was on identifying and isolating mechanisms forcing three-dimensional vertical circulations within the cyclone and its larger-scale environment. This objective was to be addressed through analysis of the output from a regional-scale numerical weather prediction model, which would provide four-dimensional dynamically consistent datasets necessary for the application of complex diagnostic equations.

In selecting cases for study, it was proposed to give priority to those that were extensively documented and scrutinized by the synoptic community, allowing application of novel and unfamiliar diagnostic approaches on well-understood cases. Specific issues to be pursued were: (i) determining whether conventional quasi-geostrophic dynamics can explain the rapid evolution of ERICA-type storms qualitatively or whether more general dynamics should be invoked; (ii) quantifying the relative importance of dynamical, diabatic, and frictional processes in rapid development; and (iii) establishing the extent to which rapid development is an exceptional response to ordinary forcing or an ordinary response to exceptional forcing. Following the initiation of the research project, it was decided to broaden the scope of the research, both to take advantage of unforeseen opportunities and to compensate for unanticipated delays, the latter involving the recruitment of highly qualified graduate students and the development of the appropriate diagnostic tools for performing the proposed research. A concise summary of each task completed during the period of the contract is now presented:

1) Participation in the Field Phase of ERICA

The principal investigator, staff, and graduate students of the Department of Atmospheric Science, State University of New York at Albany, participated extensively in ERICA field operations. In retrospect, the principal investigator is particularly proud of the contribution of the SUNY/Albany research group to the success of the field phase of ERICA. The following list of participants is based on an OMNET message from Professor Carl Kreitzberg to the ERICA bulletin board on 15 March 1990. The first number refers to the IOP; the second to the flight within the IOP. The asterisk identifies the Airborne Mission Scientist for a particular flight.

Dan Keyser	2-1*, 3-4*, 4-2, 5-4, 7-2*
Gerry Bell	5-2, 7-1
Greg Hakim	6P
Haig Iskenderian	2-1, 3-4
Anton Seimon	2-1, 3-4, 4-2, 4-5, 6P, 7-2

In addition to the main field program, SUNY/Albany personnel participated in the P-3 engineering flight of 24 January 1988 (Dan Keyser) and the Pre-ERICA Test IOP of 25-27 January 1988 (Gerry Bell and Bob Iacovazzi).

2) Theoretical Study of Cyclogenesis

This task, performed in collaboration with Professor J. A. Zehnder of the University of Arizona, utilized a two-dimensional, quasi-geostrophic, adiabatic, frictionless, f-plane channel model to study the role in rapid cyclogenesis of potential vorticity anomalies based at the tropopause and surface, and extending into the interior troposphere. The former correspond physically to tropopause folds and the latter to latent-heat-induced potential vorticity maxima. It was found that the proper superposition of these potential vorticity anomalies results in a much shorter time scale for cyclogenesis (significant surface development within 18 h) than in the classic Eady model of cyclogenesis characterized by uniform interior potential vorticity and small-amplitude initial perturbations (significant surface development requires at least 2 - 3 d). It is emphasized that this mechanism does not require the release of latent heat, which would be expected to further hasten the deepening process. A significant outcome of this study is the clarification that the unrealistically long time scale for cyclogenesis in conventional theoretical models can be attributed to simplified initial conditions constrained by the uniformity of potential vorticity. Thus, this study suggests that the rapidity of explosive maritime cyclogenesis is due in part to properly configured initial disturbances, as well as latent heat release and weak dynamic stability. This research is reported in detail in a journal article by Zehnder and Keyser (1991).

3) Development of Vertical Circulation Diagnostics

This task of the research effort has focused on the development of diagnostic methodologies for three-dimensional vertical circulations using as a test case an adiabatic, frictionless, f-plane, primitive-equation channel model of an amplifying baroclinic wave and associated cyclone and fronts. The rationale for concentrating developmental efforts on such an idealized simulation, rather than proceeding directly to simulations based on real data as originally proposed, was the unexpected similarity between the low-level frontal structure in the idealized channel model and that described in analyses from the Pre-ERICA Test IOP of January 1988 performed by Dr. M. A. Shapiro and collaborators. The extent of the agreement suggests that the results and interpretations derived from diagnosing the channel simulation may be sufficiently applicable to observed oceanic cyclones to be of physical interest in their own right. Nevertheless, the main emphasis of this task, the development of novel diagnostic techniques for representing and diagnosing vertical circulations in three dimensions, has continued unchanged.

The first major accomplishment of this task has been the use of a vector streamfunction to represent three-dimensional vertical circulations, affording the objective partitioning of vertical circulations into cross- and along-front components. This approach facilitates the rigorous identification of frontal circulations in a three-dimensional context for what is believed to be the first time. The potential significance of this outcome is that two-dimensional dynamical interpretations of frontogenesis and frontal circulations, strictly applicable to highly idealized straight-line flow configurations, may carry over to realistic three-dimensional jet-front and surface frontal systems found within intense maritime cyclones. Further documentation of this aspect of the research project is provided in the article by Keyser et al. (1989).

The second major accomplishment of this task is the development and application of a generalized form of the Sawyer-Eliassen frontal circulation equation applicable to three dimensions. This formalism opens up the possibility of addressing the conjecture that two-dimensional dynamical interpretations of frontogenesis and frontal circulations may be qualitatively applicable in three-dimensional flow configurations characteristic of intense maritime cyclones. Application of the generalized Sawyer-Eliassen equation reveals that the vertical circulations in the idealized rapidly developing midlatitude cyclone simulated in the channel model are strongly frontal in character, essentially confined to the vertical plane transverse to regions of concentrated baroclinicity. This result is supported further by partitioning the Q-vector forcing of the quasi-geostrophic omega equation into components associated respectively with frontogenesis and rotation of the potential temperature field. This partitioning indicates that frontogenesis forces banded patterns of ascent and descent in frontal regions, whereas rotation forces a synoptic-scale dipole pattern in the vertical motion field. Both results appear to support the hypothesis that rapid deepening may occur primarily on the frontal scale and through vertical circulations oriented transverse to the warm front poleward and eastward of the developing storm. Further investigation of this hypothesis is underway (M.S. thesis research of J. A. Chapman), involving application of the diagnostic methodologies developed in this portion of the research to the QE II and ERICA IOP-4 storms simulated using the Penn State/NCAR MM4 regional-scale numerical weather prediction model.

The work involving development and application of the generalized Sawyer-Eliassen equation was presented by D. Keyser at the Seventh Extratropical Cyclone Project Workshop (Keyser and Schmidt, 1988) and is about to appear in **Monthly Weather Review** (Keyser et al., 1992a). The work involving partitioning the Q vector into cross- and along-front components (Keyser et al., 1992b) is about to appear as well. Preliminary efforts in developing extensions to the quasi-geostrophic omega equation, which may be applied in the present study of the QE II and IOP-4 storms, were summarized in poster form by W. Hao at the Fourth Conference on Mesoscale Processes (Hao and Keyser, 1991). Finally, an invited review of the theory and diagnosis of frontal circulations in two and three dimensions was presented by D. Keyser at the Conference on Fronts and Orography, Burghausen, Germany (Keyser, 1991).

4) Conceptual Model of Maritime Cyclone Structure and Evolution

This aspect of the research project was an outgrowth of a collaborative effort with Dr. M. A. Shapiro in response to an invitation to coauthor a review on observations of fronts for the Palmén Memorial Symposium in 1989. This collaboration resulted in the synthesis of a conceptual model of the low-level thermal structure of rapidly developing maritime cyclones. The conceptual model comprises four distinct stages of the cyclone life cycle: (i) incipient frontal cyclone; (ii) frontal fracture; (iii) bent-back warm front and frontal T-bone; and (iv) warm-core seclusion. The process of formulating this model was unorthodox in the respect that it is based primarily on idealized simulations of cyclogenesis using channel models (similar to that considered in task #3 above) and on a realistic simulation of the QE II storm (the same one being considered in J. A. Chapman's M.S. thesis research), with minimal

appeal to observations. Despite the unconventional approach to formulating this conceptual model, it has generated considerable interest within the synoptic community. Further research is anticipated to establish the representativeness of this model, generalize it to incorporate vertical structure within the troposphere, and to illustrate and validate the model from a dynamical perspective. The aspect concerned with dynamical validation may be performed from both vertical-circulation and potential-vorticity perspectives. The former approach is being applied in Chapman's M.S. thesis research, whereas the latter is expected to constitute a portion of the doctoral-dissertation research of G. M. Lackmann.

The conceptual model of the life cycle of rapidly deepening maritime cyclones is described in Shapiro and Keyser (1990a,b). An invited review of conceptual models of frontal and cyclone structure, which included the Shapiro-Keyser conceptual model, was presented by D. Keyser at the Third Workshop on Operational Meteorology, Montreal, P.Q. (Keyser, 1990). Finally, an invited paper on the use of numerical weather prediction models for the diagnostic study of midlatitude cyclones, which emphasized the maritime problem, was delivered by D. Keyser at IAMAP 89--Fifth Scientific Assembly of the International Association of Meteorology and Atmospheric Physics, Reading, U.K. (Keyser, 1989).

5) Satellite-Derived Classification Scheme for Rapid Maritime Cyclogenesis

The reliance by forecasters on satellite imagery to detect rapid cyclogenesis in data-sparse oceanic regions such as the western North Atlantic suggested that systematic study of conventional satellite imagery for ERICA-type storms might be of practical utility. Furthermore, it was felt that, if characteristic signatures in satellite imagery could be identified, dynamical interpretation of these signatures might lead to original or modified insights into the process of rapid cyclogenesis. Interest in this problem led to a M.S. thesis project by M. S. Evans, coadvised by Professor L. F. Bosart. Four categories of development were identified from the subjective examination of satellite imagery of 46 cyclones over the western North Atlantic satisfying the ERICA deepening criterion of at least a 10 mb sea-level pressure fall in 6 h. These categories are referred to as the "emerging cloud head," the "comma cloud," the "left exit," and the "instant occlusion." The first of these is characterized by the emergence of a cloud head from underneath an "S"-shaped cirrus band; the second by development of a comma structure independent of a subtropical cirrus band; the third by development in the left-exit region of a jet streak and the subsequent merger of two separate cloud areas prior to rapid deepening in association with a diffluent trough; and the fourth by the merger of two distinct cloud areas in association with a confluent trough.

Detailed diagnostic examination of five of the 46 ERICA-type storms revealed that rapid deepening generally coincides with the superposition of maxima of advection of geostrophic shear and curvature vorticity over the low center. Rapid deepening typically occurs on the unstable (equatorward) side of enhanced horizontal gradients of the vertical gradient of equivalent potential temperature in the 1000-700 mb layer and of equivalent potential vorticity at

850 mb, indicating the possible roles of upright and slantwise convection in the deepening process. Finally, the evolution of the cloud pattern correlates well with temperature advection by the storm-relative flow at 700 mb and with the alignment of the dilatation axes of the upper-level flow.

Results of this component of the research have been presented at the First International Symposium on Winter Storms (Evans et al., 1991) and are described in detail in the M.S. thesis by Evans (1991).

Graduate Students:

Michael S. Evans; M.S. received December 1991.
Jeffrey A. Chapman; M.S. in progress.
Gary M. Lackmann; Ph.D. in progress.

Thesis:

Evans, M. S., 1991: A satellite-derived classification scheme for rapid maritime cyclogenesis. M.S. thesis, Department of Atmospheric Science, State University of New York at Albany, 181 pp.

Refereed Publications:

Keyser, D., B. D. Schmidt, and D. G. Duffy, 1989: A technique for representing three-dimensional vertical circulations in baroclinic disturbances. **Mon. Wea. Rev., 117,** 2463-2494.

Shapiro, M. A., and D. Keyser, 1990a: Fronts, jet streams and the tropopause. Extratropical Cyclones, Palmén Memorial Volume, C. W. Newton and E. O. Holopainen, Eds., 167-191.

Zehnder, J. A., and D. Keyser, 1991: The influence of interior gradients of potential vorticity on rapid cyclogenesis. **Tellus, 43A,** 198-212.

Keyser, D., B. D. Schmidt, and D. G. Duffy, 1992a: Quasi-geostrophic diagnosis of three-dimensional ageostrophic circulations in an idealized baroclinic disturbance. **Mon. Wea. Rev., 120** (in press).

Keyser, D., B. D. Schmidt, and D. G. Duffy, 1992b: Quasi-geostrophic vertical motions diagnosed from the along- and cross-isentrope components of the Q vector. **Mon. Wea. Rev., 120** (in press).

Technical Memorandum:

Shapiro, M. A., and D. Keyser, 1990b: Fronts, jet streams, and the tropopause. NOAA Technical Memorandum ERL WPL-182, 75 pp.

Conference Proceedings and Presentations:

Keyser, D., and B. D. Schmidt, 1988: Diagnosis of three-dimensional frontal circulations in an idealized baroclinic wave. Presented by D. Keyser at the Seventh Extratropical Cyclone Project Workshop, Newtown Square, PA, on 10/18/88.

Keyser, D., 1989: Numerical models of midlatitude cyclones: A mesoscale perspective. IAMAP 89--Fifth Scientific Assembly of the International Association of Meteorology and Atmospheric Physics, Mesoscale Processes in Extratropical Cyclones, August 7-9, 1989, Reading, U.K., MP-14--MP-18 **(invited paper)**.

Hao, W., and D. Keyser, 1990: A diagnostic study of three-dimensional vertical circulations in an idealized midlatitude cyclone. Preprints Fourth Conference on Mesoscale Processes, Boulder, CO, Amer. Meteor. Soc., 92-93.

Keyser, D., 1990: Fronts in the atmosphere. Preprints Third Workshop on Operational Meteorology, Montreal, P.Q., Canada, Atmospheric Environment Service and Canadian Meteorological and Oceanographic Society, 16-35 **(invited paper)**.

Evans, M. S., D. Keyser, and L. F. Bosart, 1991: A satellite-derived classification scheme for rapid maritime cyclogenesis. Presented by M. S. Evans at the First International Symposium on Winter Storms, Amer. Meteor. Soc., New Orleans, LA, on 1/17/91.

Keyser, D., 1991: A review of the theory and diagnosis of frontal circulations in two and three dimensions. Presented at the Conference on Fronts and Orography, Burghausen, Germany, on 6/12/91 **(invited paper)**.